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## Testing the Supernova, Cepheid, and Early-type Galaxy Distance Scales

J. P. Blakeslee

*Department of Physics and Astronomy, Johns Hopkins University*

**Abstract.** I summarize recent work comparing relative distances measured to individual galaxies with independent methods. The comparisons include: ground-based surface brightness fluctuation (SBF) and fundamental plane distances to 170 galaxies, distances predicted from galaxy velocities and the inferred gravity field, HST SBF measurements to seven early-type hosts of Type Ia supernovae, and ties of the Cepheid distance scale to early-type galaxies. Independent calibrations for some methods provide interesting constraints on the Cepheid zero point.

### 1. Early-type Galaxy Comparisons: SBF versus FP

The two most frequently applied early-type galaxy distance indicators are the fundamental plane (FP, and the related  $D_{n-\sigma}$ ) and surface brightness fluctuations (SBF) methods. In a recent study (Blakeslee et al. 2001, 2002), we used  $V$ - and  $I$ -band data from the ground-based SBF Survey (Tonry et al. 2001) to calculate FP photometric parameters for 170 galaxies with velocity dispersions available in the homogenized SMAC catalogue (Hudson et al. 2001). To our knowledge, this is the largest galaxy-by-galaxy comparison of different standard candle/rod distance methods to date. Fig. 1a shows the comparison.

Overall the distance agreement was good, but several low-luminosity, S0 galaxies had systematically low FP distances, probably due in part to younger ages and lower mass-to-light ratios, although aperture effects may also contribute. The SBF distances are tied to the Cepheids via measurements in spiral bulges, while the FP distances are tied to the Hubble flow via distant clusters; the Hubble constant that results from this comparison is  $H_0 = 68 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . However, we also derived independent distances for these galaxies based on their velocities and the gravity field inferred from the redshift-space galaxy density; the resulting comparison with SBF yields  $H_0 = 74$  (Fig. 1b), formally discordant at the  $2\sigma$  level with the FP-SBF result, but within the range of the systematic uncertainties in the various ties.

Another interesting facet of this work relates to the “fluctuation number”  $\bar{N} \equiv \bar{m} - m_{\text{tot}}$ , which measures the galaxy luminosity in units of the weighted mean stellar luminosity.  $\bar{N}$  correlates tightly with stellar velocity dispersion; it also correlates with galaxy color and is independent of Galactic extinction. Interestingly, SBF distances calibrated using the properties of  $\bar{N}$ , such as those shown in Fig. 1b, can be viewed as a hybrid of SBF and FP distances, and may be more accurate than those calibrated from galaxy color alone. We plan to investigate these issues in more detail.

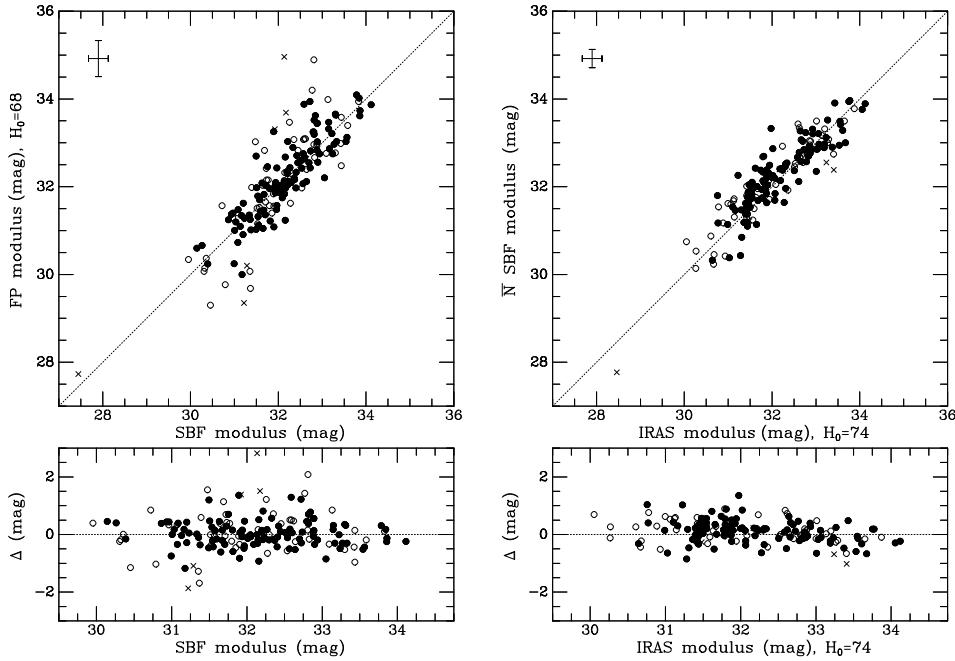


Figure 1. (a) Comparison of FP and SBF distance moduli for the 170 galaxies in the cross-matched SBF-SMAC survey samples (from Blakeslee et al. 2002). The lower panel shows distance residuals. Filled circles represent true ellipticals, while open circles represent S0s. Six galaxies having systematically uncertain FP or SBF distances are shown as crosses. (b) Same as (a), but for the comparison of  $\bar{N}$ -calibrated SBF distances with those predicted from the observed galaxy density field in redshift space (Virgo core galaxies have been assigned the systemic velocity).

## 2. Cepheid Distances to Early-type Galaxies?

Cepheids occur only in spirals and other late-type, star-forming galaxies. However, the most massive virialized structures in the nearby universe (e.g., the Virgo, Fornax, and Centaurus clusters), are overwhelmingly dominated by early-type galaxies. Although some spirals appear in projection against the Virgo core, the various secondary indicators tied to the Cepheid scale indicate that these galaxies are not at the same distance as the core ellipticals (e.g., Tonry et al. 2000; Ferrarese et al. 2000; Kelson et al. 2000; Blakeslee et al. 2002). Alternatively, it may be that the secondary indicators are yielding systematically different results for the calibrating spirals and the target ellipticals.

We have an ongoing Cycle 10 WFPC2 program to calibrate the early-type galaxy distance scale via Cepheid distances to late-type galaxies that are physically associated with ellipticals. The target galaxies are the NGC 4647/NGC 4649 pair (Fig. 2a) and NGC 5128 (Cen A), an elliptical with a central dust lane and associated star formation, apparently resulting from the incursion of a gas-rich dwarf. The Cen A Cepheid observations have yielded more than 60 superb Cepheids, making this one of largest high-quality HST Cepheid data sets. At present, we are still finalizing the analysis, but Fig. 2b shows some example light curves; differential extinction within Cen A is a major issue for this program.

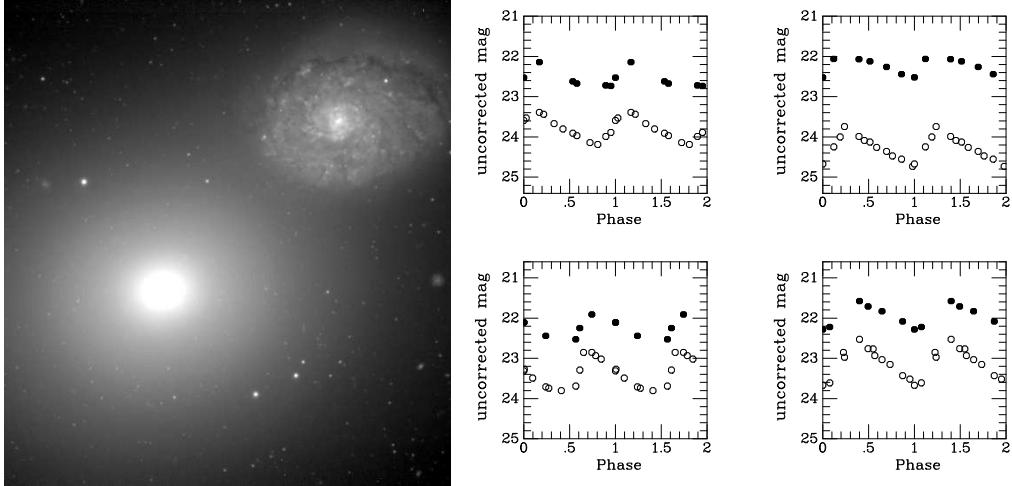


Figure 2. (a) NGC 4649/4647: one of the early-/late-type pairs targeted by our program to calibrate elliptical galaxy distances from Cepheids. (b) Some example light curves for NGC 5128 (Cen A), provided by L. Ferrarese. The magnitudes have not been corrected for internal extinction.

### 3. SNe Ia versus SBF

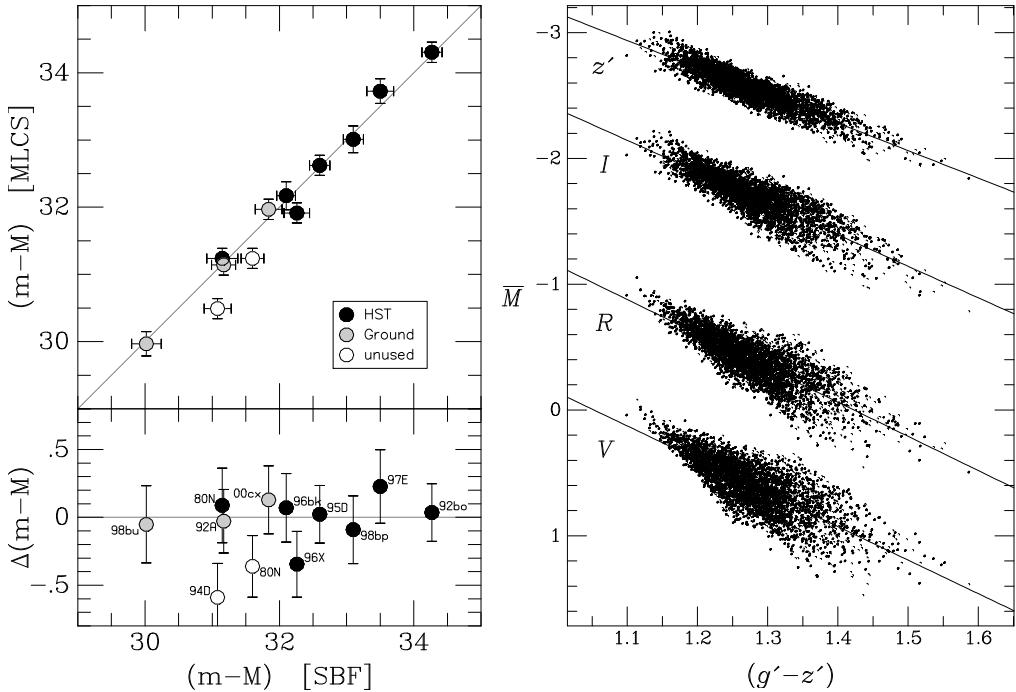
SBF and Type Ia supernovae (SNe Ia) studies have in the past disagreed on  $H_0$  at the  $\sim 20\%$  level, which is surprising for two methods that routinely achieve 5–10% internal accuracy. The excellent resolution of HST provides an enormous advantage over ground-based data for SBF studies, and we have recently used WFPC2 to measure high-quality HST/WFPC2 SBF distances to seven early-type galaxies that have hosted well-observed SNe Ia (Ajhar et al. 2001).

The results showed excellent agreement in the relative distances, but an offset of  $\sim 0.25$  mag in zero points, which we traced to the different, and indeed dissonant, compilations of Cepheid distances used in the past for the respective zero-point calibrations of the two methods. When calibrated consistently, SBF and SNe Ia also agree in an absolute sense (Fig. 3a) and give  $H_0 \approx 73$ . This is the first time the agreement has been demonstrated through a direct comparison of statistically significant samples of SBF and SNe Ia galaxy distances.

### 4. The Zero Point Problem

The most pressing problem in the measurement of extragalactic distances appears to be systematic uncertainties in the zero points. We have seen that there is significant uncertainty in the zero-point tie of the early-type galaxy distance scale to Cepheids, but perhaps even greater is the uncertainty in the Cepheid zero point itself, in part due to the poorly-constrained LMC distance.

Stellar population models can be used to predict SBF magnitudes and colors for a large range of metallicities and ages (e.g., Blakeslee, Vazdekis, & Ajhar 2001b). These models reproduce the observed SBF colors and behaviors very well, but predict an SBF zero point fainter than the Cepheid-calibrated one by  $0.2 \pm 0.1$  mag in  $I$  (the only band in which SBF is directly tied to the Cepheids via spiral bulges). However, the model and empirical zero points would come into



**Figure 3.** (a) SNeIa distance moduli from the multi-color light curve shape method are plotted versus SBF distance moduli. The two “unused” galaxies had SNe with unusual light curves. Both methods are tied to the “final” Key Project Cepheid distances (Freedman et al. 2001). (b) Absolute SBF magnitude  $\bar{M}$  in various bands is plotted against  $(g' - z')$  color index for the composite stellar population models of Blakeslee et al. (2001b). The models indicate that the Cepheid distance scale should be revised down by 0.1–0.2 mag. Interestingly, they also predict that  $z'$  should be the best optical bandpass for SBF.

close agreement if the Cepheid scale were revised to agree with the dynamical distance to the NGC 4258 water maser (Herrnstein et al. 1999), for example, by changing the assumed LMC distance modulus from 18.5 to 18.3 mag. Further refinements of the models should provide more stringent tests of the distance scale and guide future SBF programs (Fig. 3b).

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